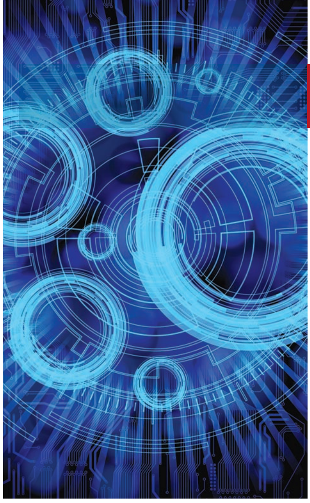

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Physical-Cyber-Social Computing: An Early 21st Century Approach

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Technology plays an increasingly important role in facilitating and improving personal and social activities, engagements, decision making, interaction with physical and social worlds, insight generation, and just about anything that humans, as intelligent beings, seek to do. We've used the term *computing for human experience* (CHE)[1] to capture technology's human-centric role. CHE emphasizes the unobtrusive, supportive, and assistive part technology plays in improving human experience; here, technology "takes into account the human world and allows computers themselves to disappear in the background."[2] We can distinguish this from Licklider's vision of human-computer collaboration, Eglebert's vision of augmenting human intellect and—more recently—ambient intelligence, and Vannever Bush's and McCarthy's machine-centric vision of making computing more intelligent so that it thinks and behaves like humans.

Here, we present an emerging paradigm called *physical-cyber-social* (PCS) computing. It encompasses a holistic treatment of data, information, and knowledge from the PCS worlds to integrate, correlate, interpret, and provide contextually relevant abstractions to humans. We view PCS as the next phase of computing systems, building on current progress in cyber-physical systems, socio-technical systems, and cyber-social systems to support CHE. PCS incorporates deeper and richer semantic interdependence and interplay between sensors and devices at physical layers; richer technology-mediated social interactions; and the gathering and application of collective intelligence characterized by massive and contextually relevant background knowledge and advanced reasoning to bridge machine and human perceptions. PCS computing requires that we move away from traditional data processing to multitier computation along the data-information-knowledge-wisdom (DIKW) dimension, which supports reasoning to convert data into abstractions that are more familiar, accessible, and understandable to humans.

We illustrate PCS computing for healthcare with a focus on semantic perception,[3] which converts low-level, heterogeneous, multimodal, and contextually relevant data into higher-level abstractions that can provide insights and assist humans in making complex decisions.

Case Study

Consider the case of Ram, a 60-year-old Asian male, who receives a blood pressure screening from his doctor and discovers that the reading is slightly higher than expected (90 diastolic, measured in mmHg). Let's look at two questions that Ram might have: What is the normal blood pressure of an Asian male of his age? What is the best way to manage a diastolic blood pressure of 90? To answer these questions, we need access to physiological observations obtained from other people with similar characteristics and demographics (physical). We should also consider the ethnic, social, cultural, and economic background for similarity (social). Moreover, in addition to expert knowledge, the knowledge and experience of similar people dealing with the same health issue are important (cyber). Neither an average doctor nor current cyber-physical systems can answer these questions, but PCS computing can address them in a holistic manner. Patient empowerment and personalized medicine are important in reducing the current $2.6 trillion in annual healthcare costs in the US (see www.kaiseredu.org/issue-modules/us-health-care-costs/background-brief.aspx), of

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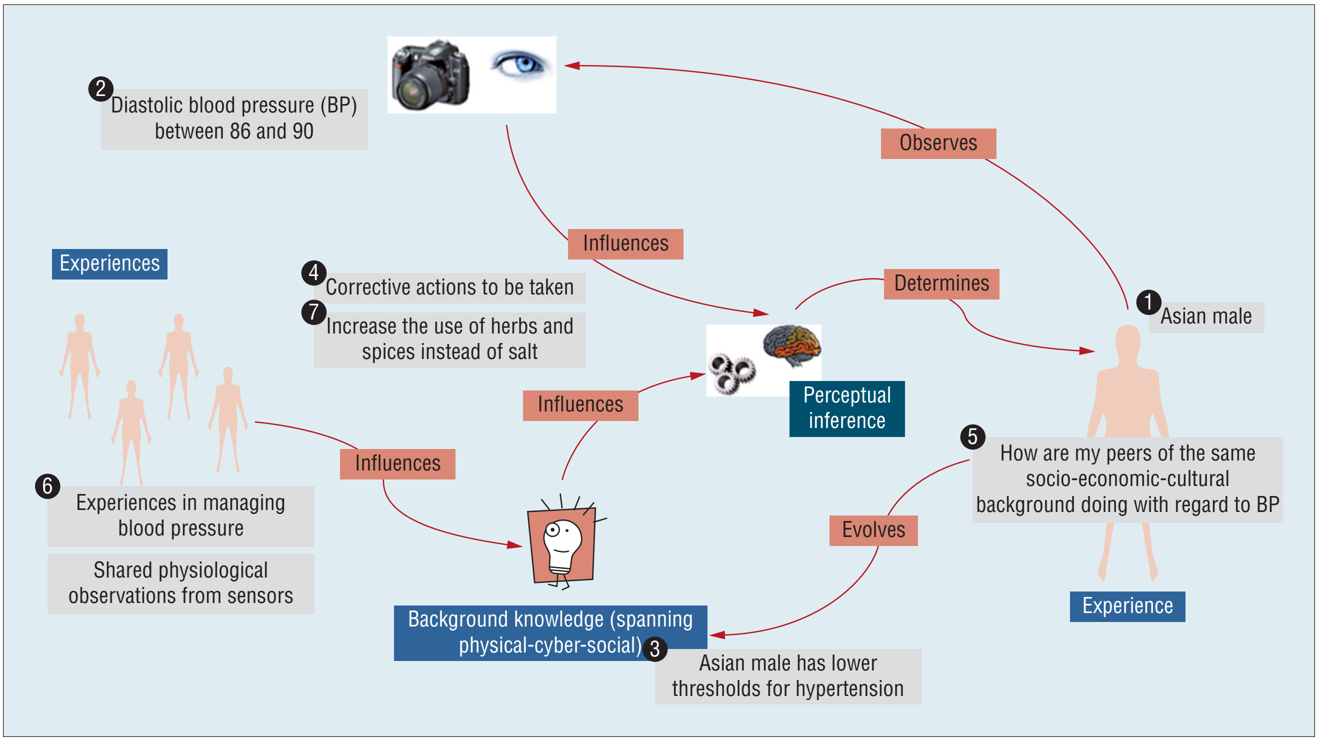

Figure 1. Physical-cyber-social (PCS) computing exemplified with a healthcare example. The vision of PCS computing incorporates observations, experiences, background knowledge, and perceptions.

which 75 percent goes to managing chronic diseases (including hypertension). This is one of many examples in which PCS computing can make a significant dent.

Current manifestations of systems involving PCS components are loosely connected. Quantified Self (quantifiedself.com), for example, involves a community of enthusiasts who monitor health-related parameters such as food intake, exercise, and sleep, and analyze them to derive insights that are valuable for their health, fitness, and overall well-being. The community shares these insights through articles, videos, and social events organized in many cities around the world.

In our example, Ram collects observations on his blood pressure and presents visualization at a Quantified Self event. However, this community still can't answer his questions without knowledge and experiences from others with a similar condition. Observations from these systems are too often stove-piped due to many difficult challenges, such as the semantic integration and sharing of heterogeneous sensor observations or disparate service providers. Current integration and interaction between PCS worlds is brittle and involves limited syntactic interoperability or integration rather than semantic integration. These two challenges have led to significant human involvement in making sense of observations from contextually relevant information.

PCS Computing

Figure 1 depicts a human-centric vision of PCS computing involving observations, experiences, background knowledge, and perceptions. The observations from the physical world help us derive perceptions of our environment. These perceptions are strongly influenced by our background knowledge (that is, our beliefs and understanding of the world) and current observations. By analyzing the observations in the context of our background knowledge, we orient ourselves toward subsequent actions. Decisions regarding which action to take are based on evidence and our experiences. Finally, we take an action, and the process repeats.

Perceptions determine our experience and evolve our background knowledge. Experiences from the social world influence that knowledge and indirectly shape our perceptions and subsequent experiences. All these interactions heavily depend on human cognitive processing to analyze the connections between PCS worlds. For its computational counterpart, John Boyd's concept of *observe, orient, decide,* and *act* (the OODA loop; http://en.wikipedia.org/wiki/OODA_loop) provides a useful context for intelligently processing observations from PCS worlds. Consequently, we can characterize the PCS computing process as an OODA-loop process (and view Figure 1 as an OODA loop).

The PCS computing vision integrates observations, knowledge, and experiences across PCS layers to provide

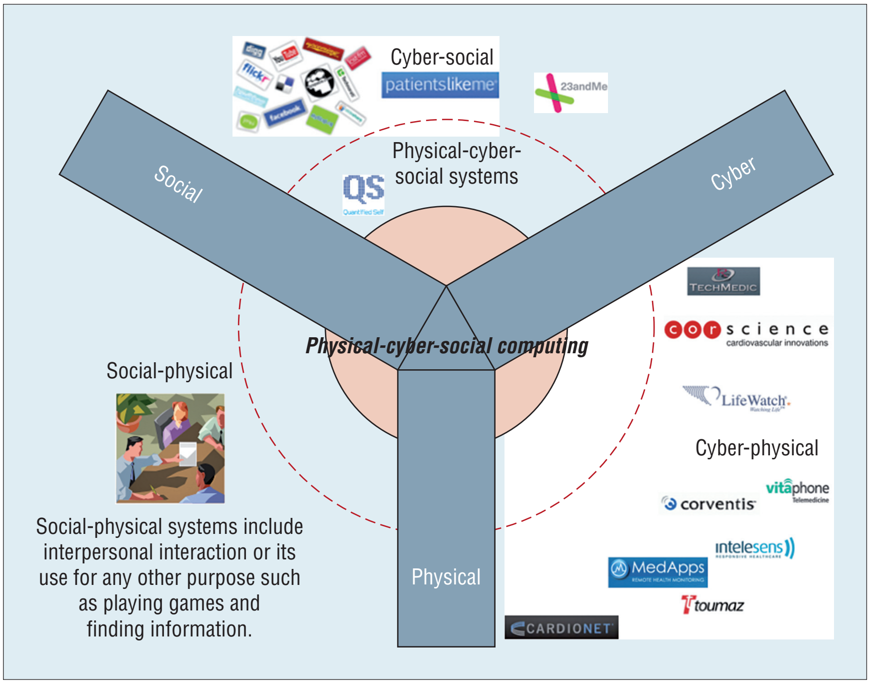

Figure 2. Physical-cyber-social (PCS) computing at the heart of physical, cyber, and social worlds. The outer and inner circles represent systems with shallow and deep integration between PCS layers, respectively.

a more holistic computational framework. It's supported by the expanding Internet of Things (an improved ability to observe the physical world), cyberspace (an improved ability to access a massive repository of background knowledge), social media (improved access to social knowledge), and the emergence of new capabilities in contextual information processing and reasoning. For this, PCS computing relies on deeper semantic integration and interplay between the three layers, as Figure 2 shows. The outer and inner circles represent systems with shallow and deep integration between PCS layers, respectively.

PCS Operators

PCS computing will be possible due to a series of PCS operators that span the DIKW triangle.[4] Figure 3 illustrates two such operators, which we describe next.

Horizontal Operators

To more deeply understand the PCS domains, we must semantically integrate heterogeneous, multimodal observations. Horizontal operators map multimodal PCS data into concepts to support semantic integration within each level of the multitier computation along DIKW dimensions. Heterogeneous observations in healthcare include machine sensor observations (physical measurements, such as blood pressure and heart rate), self-observations (subjective thoughts, feelings, moods, and so on), social observations (from a network including family, friends, and colleagues), and demographic observations (aggregated characteristics of the population with similar attributes or lineage). PCS horizontal operators integrate all these observations using semantics-empowered integration techniques.

Vertical Operators

Vertical operators translate observations from low-level data to a high-level knowledge. They're unique with respect to existing techniques for ascending through the DIKW triangle in two ways: first, the operator is agnostic about the source of the observations, and second, the knowledge base isn't limited to a formal ontology—it spans everything from statistical knowledge to social experiences. An example of this is semantic perception.[3,5,6] However, we must expand this notion to envision machine perception that can use background knowledge found throughout the Web (cyber) to integrate and interpret observations from PCS dimensions. This type of perception is far more encompassing and far-reaching than any single person's abilities.

Example Healthcare Application

One challenge in PCS computing is collecting massive amounts of data from the PCS dimensions, which further adds to the current big data challenge. PCS computing approaches this using horizontal operators to deal with variety and veracity, and vertical operators to deal with volume and velocity.

Let's again look at Ram's hypertension to illustrate PCS computing for personalized health and patient empowerment. Existing knowledge in the cyberworld will tell us that the US National Institutes of Health considers a person with diastolic pressure of 80 to 89 mmHg pre-hypertensive, and a reading greater than 90 mmHg to be stage I hypertensive (www.nhlbi.nih.gov/health/health-topics/topics/hbp/). Additional background knowledge indicates that South Asians, such as Ram, have a higher incidence of cardiovascular disease, and discussions in social groups indicate that many experts advise that a safe blood pressure for South Asians would be less than 130/80 mmHg.

PCS computing could answer Ram's questions introduced in the beginning of the article. Ram's diastolic blood pressure between 86 and 90 mmHg

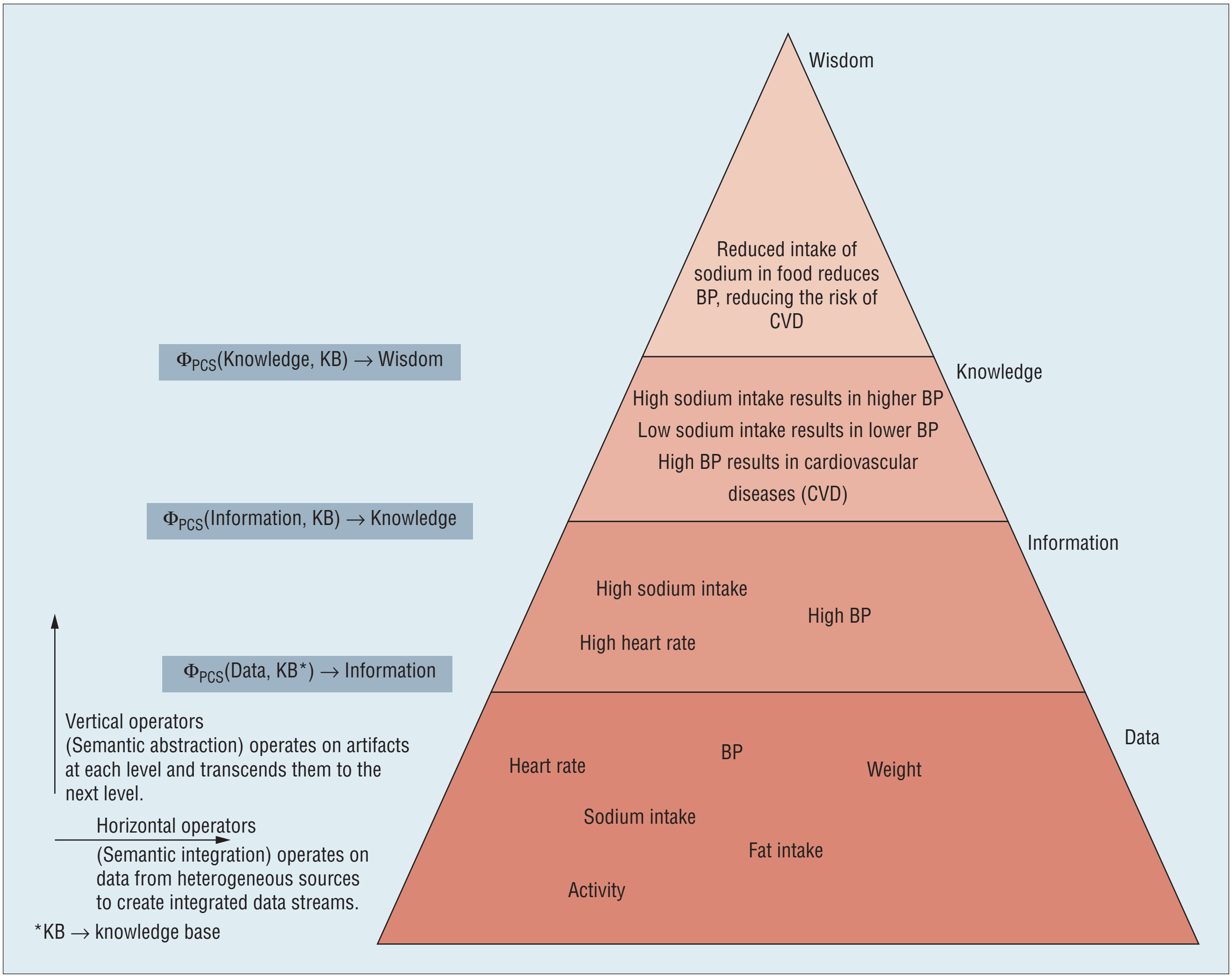

Figure 3. The data-information-knowledge-wisdom (DIKW) triangle. We can use the triangle to illustrate two types of PCS computing operators, exemplified here for a healthcare domain.

indicates that he's pre-hypertensive. However, knowledge about similar people with the same ailment indicates that South Asian males have lower thresholds than average for hypertension, or have a lower target than the general population. This background and social knowledge influences the perception process in inferring a higher-risk score. PCS computing can provide deeper insights and corrective actions. It can integrate observations, experiences, and knowledge from people with similar ethnic, social, cultural, and economic backgrounds. Considering all these aspects while computing a solution, PCS computing will provide effective, personalized, and actionable information to Ram. Being a South Asian male, it's recommended that he reduce his salt intake and substitute it with spices.

PCS computing captures a synergetic interaction between computing and human experience while providing holistic computational solutions encompassing the PCS dimensions. The future of technology won't be primarily about asking questions and receiving relevant documents for search queries. CHE enabled by PCS computing represents a paradigm shift from search-based technology to solution-based technology in which knowledge is generated by continuously observing human activities within the PCS worlds, and we can use this knowledge to improve human experience. That is, PCS computing will translate data, information, and knowledge from PCS dimensions into action, leading to the emergence of a global brain (www.slideshare.net/timoreilly/towards-a-global-brain-7968429).

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